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THE PROBLEM OF WAVE ACTION ON EARTH SLOPES

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PAPERS

THE PROBLEM OF WAVE ACTION ON EARTH SLOPES

By Martin A. Mason,[1] Assoc. M. ASCE

Synopsis

A brief resumé of current knowledge and research on wave action on earth slopes and the possible application of World War II developments, particularly in regard to methods for predicting wave action, is discussed. The Sverdrup-Munk method of predicting wave height and period from synoptic weather maps is recommended as a substitute for the older purely empirical methods. The Iribarren formula for the calculation of sizes of stone required on various slopes for protection against wave action is recommended as the only available satisfactory method of design. An outline of necessary further study and research is presented.

Current Knowledge

Wave action is the primary factor to be considered in the design of slope protection for earth dams. It is precisely this factor which is least known or understood by the engineering profession. Students of the subject have concentrated their attention on the empirical formulas for predicting wave action which have been used in the past; and have been criticized, perhaps justly, for its failure to have made use of wartime advancements in the knowledge of waves.

In support of the profession's apparent neglect of wartime developments of wave knowledge, it must be noted that much of the knowledge was cloaked in military secrecy for a long time. Relatively little information on the engineering applications is available even now (1950). The only confirmation of the relationships developed by H. U. Sverdrup and W. H. Munk,[2] which can be cited in support of their applicability to reservoir situations lies in the lagoon

Note.—Written comments are invited for publication; the last discussion should be submitted by May 1, 1951.

[1] Chf. Eng. and Research Branch, Beach Erosion Bldg., Washington, D. C.

[2] "Wind Waves and Swell Principles in Forecasting," by H. U. Sverdrup and W. H. Munk, *Miscellaneous Publication No. 11275*, U. S. Hydrographic Office, Washington, D. C., 1946.

tests made by J. W. Johnson, M. ASCE, at Abbotts Lagoon (Calif.), on which a complete report has been published.[3]

The Sverdrup-Munk relationships were developed for application to oceanic situations, where clearly defined fetches of hundreds of miles, wind velocities of 60 knots, and wind duration times of many hours represent the magnitudes involved. In the development of the relationships certain theoretical considerations were used to develop equations that involved constants. These constants were then evaluated through the use of previously observed characteristics of ocean waves. Continued observations of waves have been made and they have been used to verify the values of the constants. Under these circumstances the applicability of the Sverdrup-Munk relationships to the radically different reservoir situation appears questionable until positive evidence is available to demonstrate the applicability. Additional tests to confirm the applicability of these relationships to various reservoir conditions are needed and until such confirmation is available the use of the relationships must be tempered with judgment.

The Corps of Engineers, United States Department of the Army, has been studying wave action in reservoirs by means of instruments installed in the reservoirs created by Fort Peck (Montana) and Denison (Texas) dams and in Lake Okeechobee (Florida) to obtain reliable data on winds, waves, wind set-up, and wave run-up. This ambitious and extensive program of carefully planned study undoubtedly will add to current knowledge a large body of factual data which can lead to a satisfactory solution (at least in part) of the more pressing problems of wave action on dam slopes. The Lake Okeechobee installation has been in operation since the fall of 1949 and the hurricane sequence has been experienced. Insufficient data have been accumulated to permit drawing conclusions and even tentative confirmation of present practices must await additional evidence.

Further Study

Further research and study of reservoir waves are important to the engineering profession. Although the exercise of judgment and the use of the existing formulas, including the Sverdrup-Munk development, represent good engineering practice in the present state of knowledge, additional and extensive study is badly needed on the following subjects:

1. Methods for determining in advance of construction the characteristics of the wave action to be expected in reservoirs created by dams;
2. Details of wave action on dam slopes protected by riprap, paving, or other covers; and
3. Formulation of design requirements and criteria for earth-dam slope protection to withstand the effects of wave action, weather, and reservoir drawdown.

Research on items 1 and 2 can be done concurrently to good advantage; but item 3 can be studied best only after some authoritative results are derived from studying the details of wave action on slope protection.

[3] "Relationships Between Wind and Waves, Abbotts Lagoon, California," by J. W. Johnson, *Transactions*, Am. Geophysical Union, June, 1950, p. 386.

The known factors of concern in the problem, as applied to a proposed reservoir location, will be as follows:

a. The elevations of the pool water surface under operating conditions;
b. The geography of the pool surface at the operating elevations—that is, the configuration, depths, length, and azimuths of the pool;
c. The topography of the area contiguous to the pool and of the area that has an influence on the wind structure over the pool; and
d. The location, orientation, character of material, and geometry of the upstream face of the earth dam creating the pool.

Generally, information on the velocity, direction, and duration of the wind at or near the pool level (factor *c*) will not be available; but reasonably accurate, historical, synoptic weather charts should be obtainable for any locations within the United States.

Wave Action in Reservoirs

The first problem is to determine the characteristics of the wave action to be expected in the proposed reservoir. For this purpose various purely empirical expressions are available, such as the well-known equations proposed by T. Stevenson, the late D. A. Molitor, M. ASCE, and W. P. Creager, Hon. M. ASCE, and the partly empirical expressions developed by Messrs. Sverdrup and Munk. The former expressions purport to define the maxima to be expected; the latter claim to define a "significant height and period" of a fictitious wave which is representative of the average of the highest one third of the waves to be expected. There is little conclusive evidence confirming the accuracy of any of the various formulas when applied to reservoir situations, and there appears to be sufficient doubt regarding their accuracy to justify study to confirm, reject, or modify existing controversial formulas.

In this connection it is believed that the waves of most importance in the design of slope protection are the maximum waves to be expected, assuming that these maxima will occur with sufficient frequency to be considered significant. This belief is based on the necessity for specifying maximum wave run-up as well as other wave effects. It is obvious then that the Sverdrup-munk relations must be modified to provide information on the maximum waves to be expected rather than information on an average of the one-third highest waves.

During the planning stage the only factors on which knowledge is available for computing expected maximum wave action in the reservoir are: (*a*) The planned operating pool levels; (*b*) the geography of the pool surface at operating levels; (*c*) the topography of the pool boundaries; and (*d*) the daily synoptic weather maps. The problem is to relate these factors in such a way as to arrive at a definition of maximum wave action to be expected.

Experience has shown that the purely empirical approach to a solution can be ignored. A rigorous theoretical approach appears to be practical. Research on ocean waves has proved that, with adequate weather maps, wind waves on water surfaces can be predicted if accurate relationships between the wave characteristics and the fetch, velocity, and duration of the wind are

known. These relationships can be determined theoretically from considerations of wave energy, and they have been formulated for certain oceanic situations by Messrs. Sverdrup and Munk.[2] The procedure involves the consideration of a generating area in which the waves are formed by wind action. Expressions are established for the rate of energy transfer from the wind and the rate at which wave energy advances from the generating area. From these expressions it is possible to form a differential equation from which the relationships sought are obtained as special solutions. The solutions contain three numerical constants which must be evaluated. The principal uncertainty attached to the use of the Sverdrup-Munk relationships for reservoir situations arises in evaluating these constants, since the presently assigned values were derived from oceanic situations. Relatively few observations for reservoir situations should permit the re-evaluation of the constants to fit those situations and should establish the Sverdrup-Munk relations, or a modification, as an acceptable method of predicting wave action.

Unfortunately this is not all that must be done. There must be established methods of deriving wind velocity, fetch, and duration, at or near the operating pool level from the daily synoptic weather maps. In this aspect the reservoir situation is much more complicated than the open ocean because of the effect of surrounding topography in modifying the wind structure, and the configuration of the reservoir in controlling fetch. Reservoirs can be considered as bodies of water of short fetch, with the fetch determined by the shore lines and the wind direction. Under these conditions the wave action in the reservoir depends on the velocity and direction of the wind, with wind duration usually not being a limiting factor. The possibility of simplifying the Sverdrup-Munk relationships is apparent in this case. It appears reasonably certain that observed wind data from near-by weather stations have little or no value for use in predicting formulas since local effects control the observed values, and there is no reason to believe that the winds at the observation station are effective in generating waves in a distant reservoir.

Meteorologists must be approached for the solution to this phase of the problem, which solution may be difficult to express in a generally applicable form. This part of the problem is the controlling element in a successful prediction of reservoir waves and it will be the most difficult to handle.

Wave Action on Dam Slopes

The second problem of concern is the action of waves on protected slopes. Little is known of the details of wave action on any but impermeable vertical slopes. Most knowledge of the details of wave action on protected slopes has been derived by incidental observation in nature, with little having been derived from experiments made for the purpose. There are several items of interest and importance—

1. The extent of wave uprush and backwash, for various slopes and cover material;
2. The disruptive and transporting forces associated directly with wave uprush and backwash;

3. The impact forces resulting from wave action for various slopes, slope combinations, and cover material; and
4. Secondary phenomena, such as the alternate compression and expansion of air trapped in cavities or interstices of the protective cover.

To solve all the design problems of protective cover information on these items is necessary, and it would appear to be desirable to plan any study of the two problems (wave action in reservoirs and on protected slopes) concurrently.

Engineers who have had practical experience with wave action on structures can help by supplying information on protection failures. Data on specific causes of failure, methods of failure in detail, character of wave action, and secondary effects contributing to failure are particularly needed.

The only extensive studies of these problems, known to the writer, which have resulted in generalized criteria applicable to many situations, were made by Ramon Iribarren Cavanilles.[4] Perhaps the best statement of the current knowledge of these problems lies in a quotation by Mr. Iribarren of a statement made in 1933 by E. de Castro (translated version):

> "* * * Authors of universal renown hesitate when the moment arrives to determine the slope of a rock-fill dam beaten by the waves, and justify their doubts and hesitation in the great difficulties which the problem holds. * * * The unknown force of the waves, the anomalies of storms and the heavy and grievous replies with which the sea responds to the science (sic) and prudence of the builders show that they are right. * * * At the conclusion of these lines one will have the impression that the problem is very obscure and only the ignorant can believe that it is solved. In spite of all, and until the definite truth is known there need not be lacking provisional truths, or better said, approximations to the truth."

Mr. Iribarren presents, as an example of such an approximation to the truth, a formula which fixes the slope and size of stone necessary to resist the violent beatings of the sea:

$$W = \frac{K h^3 \gamma}{(\cos \alpha - \sin \alpha)^3} (\gamma - 1)^3 \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which W is the weight of stone, in kilograms; K is a coefficient, with a value of 15 for natural rock fill and a value of 19 for artificially placed stone; h is the total height of the wave, through to crest, in meters; γ is the specific weight of stone, in tons per cubic meter; and α is the slope of the dike, measured as the angle with the horizontal. In the development of the formula, consideration has been given to the details of wave action previously noted, and logical arguments introduced to support the evaluation of the various factors in the formula. An important part of the arguments is a contention that, regardless of the slope of the structure, the waves strike at approximate normality to the slope.

Proceeding further, Mr. Iribarren states that the height of the structure should be greater than the still water level height by an amount equal to the wave height, or 1.25 times the wave height. These heights are stated to be sufficient to prevent overtopping.

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[4] "A Formula for the Calculation of Rock-Fill Dikes," by Ramon Iribarren Cavanilles, *Bulletin*, Beach Erosion Board, Washington, D. C., January, 1949.

Mr. Iribarren's work has been accorded some importance in this paper because of the great interest it has occasioned among harbor and shore control engineers concerned with the design of protective structures, and because of its obvious import to designers of protective works. In the opinion of the writer, it represents the most logical solution available for designing slope protection cover.

Summary

It is apparent that much remains to be done. Equally apparent is the fact that progress toward a closer approximation to the truth must depend on scientific studies of the intimate details of wave action on slopes rather than on empirical correlations of observational data. Much of the required research will not have an immediately discernible practical value. The studies will be difficult and expensive. Nevertheless, study and research are the only acceptable methods of obtaining the required knowledge. Perhaps nowhere in the engineering field can one find a less logical, less technical approach to an engineering problem, or larger expenditures made on the basis of well-intentioned but faulty estimates of a situation, than in the field of slope protection. Research efforts are long overdue and should be prosecuted with utmost vigor.

Acknowledgment

The substance of this paper formed part of the 1949 progress report of the Committee on Earth Dams of the Soil Mechanics and Foundations Division, through its Subcommittee on Slope Protection.[5]

[5] *Civil Engineering*, February, 1949, p. 46.

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